# The CIE 1997 Interim Colour Appearance Model (Simple Version), CIECAM97s

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## SUMMARY

TC1-34, Testing Colour Appearance Models, was established to test various models for the prediction of the colour appearance of object colours. Later, TC1-34's terms of reference were extended to include the recommendation of a single colour appearance model to be used until a demonstrably better model could be formulated. The committee decided to formulate a single model with a simple version for many practical applications and comprehensive version for a wide range of viewing conditions and phenomena. TC1-34 will continue its work testing this and other models. This report summarizes the formulation of the simple version of the CIE Interim Colour Appearance Model, CIECAM97s. The extension of this model to a comprehensive version, CIECAM97c, will be formulated and published in the future.

# CONTENTS

# 1. INTRODUCTION

In March 1996 the CIE held an expert symposium on *Colour Standards for Image Technology* in Vienna (CIE, 1996). While the symposium covered many image technology concepts for which the CIE might provide guidance or standards to assist industry, one of the critical issues was the establishment of a general-use colour appearance model. Symposium participants from industry recognized the need for a colour appearance model, but requested CIE guidance in establishing a single model that could be used throughout the industry to promote uniformity of practice and compatibility between various components in modern imaging systems.

## 1.1 Background

Colour appearance models are used to extend traditional colorimetry (e.g., CIE XYZ and CIELAB) to the prediction of the observed appearance of coloured stimuli under a wide variety of viewing conditions. This is accomplished by taking into account the tristimulus values of the stimulus, its background, its surround, the adapting stimulus, the luminance level, and other factors such as cognitive discounting the illuminant. The output of colour appearance models includes mathematical correlates for perceptual attributes such as brightness, lightness, colourfulness, chroma, saturation, and hue. Colour appearance models are used in applications such as digital colour reproduction and assessment of the colour rendering properties of light sources.

The requirements for a single model were highlighted and summarized in a presentation by Hunt (1996) made at the Vienna symposium. In that presentation, Hunt reviewed the status and historical development of various models and presented 12 principles for consideration in establishing a model. These principles, reproduced below, served as the guiding rules in the formulation of CIECAM97s.

1. The model should be as comprehensive as possible, so that it can be used in a variety of applications; but at this stage, only static states of adaptation should be included, because of the great complexity of dynamic effects.

2. The model should cover a wide range of stimulus intensities, from very dark object colours to very bright self-luminous colour. This means that the dynamic response function must have a maximum, and cannot be a simple logarithmic or power function.

3. The model should cover a wide range of adapting intensities, from very low scotopic levels, such as occur in starlight, to very high photopic levels, such as occur in sunlight. This means that rod vision should be included in the model; but because many applications will be such that rod vision is negligible, the model should be usable in a mode that does not include rod vision.

4. The model should cover a wide range of viewing conditions, including backgrounds of different luminance factors, and dark, dim, and average surrounds. It is necessary to cover the different surrounds because of their widespread use in projected and self-luminous displays.

5. For ease of use, the spectral sensitivities of the cones should be a linear transformation of the CIE $\bar{x}$, $\bar{y}$, $\bar{z}$ or $\bar{x}_{10}$, $\bar{y}_{10}$, $\bar{z}_{10}$ functions, and the $V'(\lambda)$ function should be used for the spectral sensitivity of the rods. Because scotopic photometric data is often unknown, methods of providing approximate scotopic values should be provided.

*6. The model should be able to provide for any degree of adaptation between complete and none, for cognitive factors, and for the Helson-Judd effect, as options.*

*7. The model should give predictions of hue (both as hue-angle, and as hue-quadrature), brightness, lightness, saturation, chroma, and colourfulness.*

*8. The model should be capable of being operated in a reverse mode.*

*9. The model should be no more complicated than is necessary to meet the above requirements.*

*10. Any simplified version of the model, intended for particular applications, should give the same predictions as the complete model for some specified set of conditions.*

*11. The model should give predictions of colour appearance that are not appreciably worse than those given by the model that is best in each application.*

*12. A version of the model should be available for application to unrelated colours (those seen in dark surrounds in isolation from other colours).*

The conclusion drawn at the symposium was that the CIE should immediately begin work on the formulation of such a model with the goal that it be completed prior to the AIC (International Colour Association) quadrennial meeting to be held in Kyoto in May, 1997. The CIE decided that this task would become part of the TC1-34 terms of reference. This report

details the simple version of the model agreed upon by TC1-34 at its meeting during the May, 1997 CIE Division 1 meeting in Kyoto.

There are a number of terms that require precise usage in the colour appearance field. All terms in this report follow the definitions of the *International Lighting Vocabulary* (CIE, 1987). Their typical usage in the colour appearance field is also further detailed in Fairchild (1998).

## 2. THE CIECAM97s MODEL

It is important to note that the formulation of CIECAM97s builds upon the work of many researchers in the colour appearance field. This was an important issue in TC1-34's establishment of this model as the best of what is currently available. Various aspects of the model can be traced to work of (in alphabetical order) Bartleson, Breneman, Fairchild, Estevez, Hunt, Lam, Luo, Nayatani, Rigg, Seim, and Valberg among others. Examples of these contributions include the Bradford chromatic-adaptation transform (Lam, 1985; Luo, 1997), a different exponent on the short wavelength response (Nayatani *et al.*, 1982), partial adaptation factors (Fairchild, 1996; Nayatani, 1997), cone responsivities (Estevez; see Hunt and Pointer, 1985), a hyperbolic response function (Seim and Valberg, 1986), redness-greenness and yellowness-blueness scales (Hunt, 1994; Nayatani, 1995), surround effects (Bartleson and Breneman, 1967), no negative lightness predictions (Nayatani, 1995, Fairchild, 1996), and a chroma scale (Hunt, 1994). Clearly, CIECAM97s is the result of the amalgamation of a wide range of colour appearance research.

Preliminary testing of CIECAM97s indicates that it performs as well as, if not better, than any previously published model for a wide range of experimental data (Hunt, 1997). These results will be expanded upon and published in the final report of TC1-34. The comprehensive model, CIECAM97c, will be derived from the simple model, CIECAM97s, by adding features that include (but are not necessarily limited to) the rod response, prediction of the Helson-

Judd and Helmholtz-Kohlrausch effects, and options for application to unrelated colours. It is also important to note that these models are recognized to be empirical models capable of predicting the available visual data. It is expected that anticipated scientific insights will, at some time in the future, allow the derivation of more theoretically correct models that are also capable of predicting experimental results.

## 2.1 Input Data

The model input data are the adapting field luminance in cd/m$^2$ (normally taken to be 20% of the luminance of white in the adapting field), $L_A$, the relative tristimulus values of the sample in the source conditions, XYZ, the relative tristimulus values of the source white in the source conditions, $X_wY_wZ_w$, and the relative luminance of the source background in the source conditions, $Y_b$. Additionally, the constants c, for the impact of surround, $N_c$, a chromatic induction factor, $F_{LL}$, a lightness contrast factor, and F, a factor for degree of adaptation, must be selected according to the guidelines in Table 2.1. All CIE tristimulus values are obtained using the CIE 1931 Standard Colorimetric Observer (2°) (CIE, 1986). Background is defined as the area immediately adjacent to the stimulus of interest and surround is defined as the remainder of the visual field. Surround relative luminances of greater than or approximately equal to 20% of the scene white are considered average, less than 20% are considered dim, and approximately 0% are considered dark.

Table 2.1. Selection guidelines for parameters used in CIECAM97s.

| Viewing Condition | c | $N_c$ | $F_{LL}$ | F |
|---|---|---|---|---|
| Average Surround, Samples Subtending> 4 ° | 0.69 | 1.0 | 0.0 | 1.0 |
| Average Surround | 0.69 | 1.0 | 1.0 | 1.0 |
| Dim Surround | 0.59 | 1.1 | 1.0 | 0.9 |
| Dark Surround | 0.525 | 0.8 | 1.0 | 0.9 |
| Cut-Sheet Transparencies (on a viewing box) | 0.41 | 0.8 | 1.0 | 0.9 |

## 2.2. Chromatic Adaptation

An initial chromatic adaptation transform is used to go from the source viewing conditions to corresponding colours under the equal-energy-illuminant reference viewing conditions. First, tristimulus values for both the sample and white are normalized and transformed to spectrally-sharpened cone responses, illustrated in Fig. 2.1., using the transformation

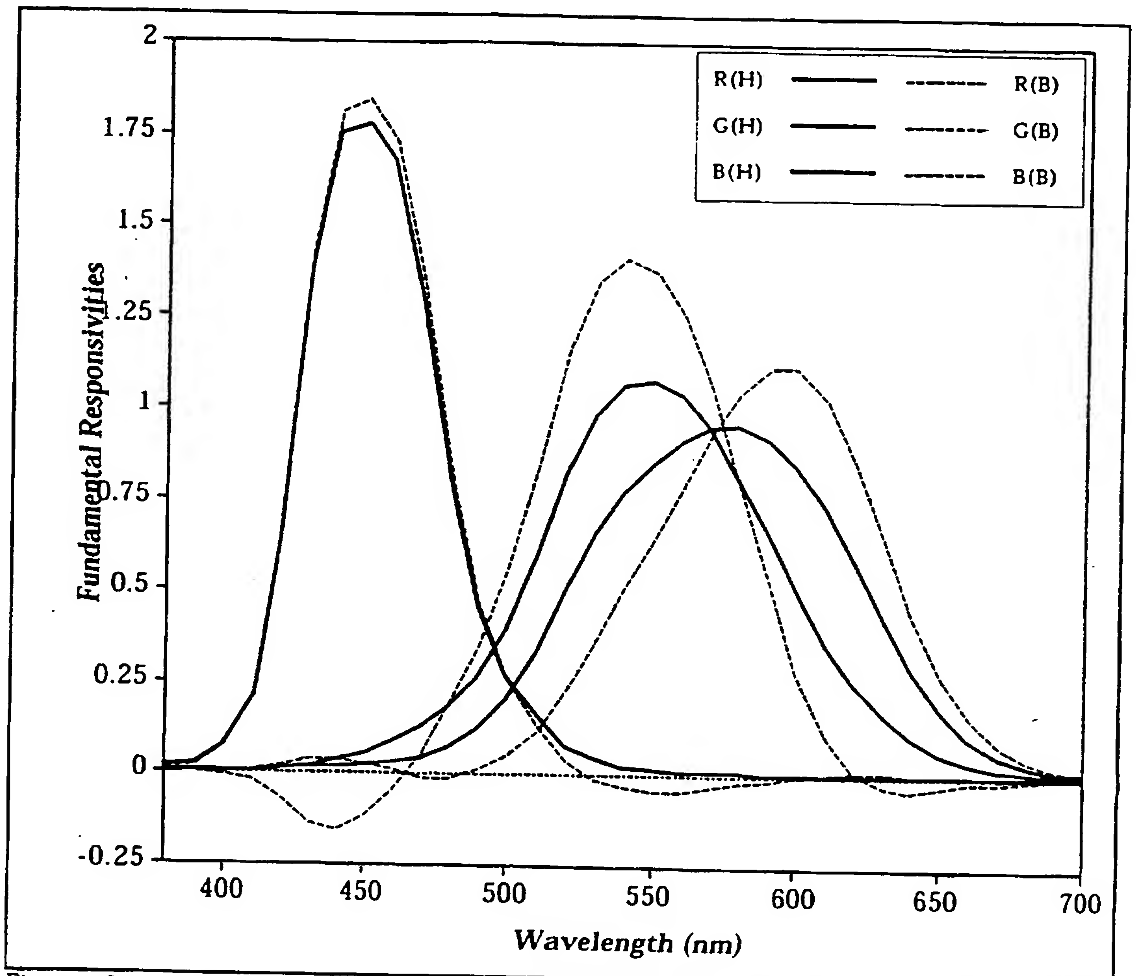


Figure 2.1. The fundamental ("cone") responsivities obtained using the Bradford transformation, $M_B$, (dashed lines) and the Hunt-Pointer-Estevez transformation, $M_H$ (solid lines).

given in Eqs. 2.1 and 2.2. Note that the forward matrix transformation given in Eq. 2.2 was applied to the spectral tristimulus values of the CIE 1931 Standard Colorimetric Observer in order to generate the curves presented in Fig. 2.1.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_B \begin{bmatrix} X/Y \\ Y/Y \\ Z/Y \end{bmatrix} \tag{2.1}$$

$$M_B = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \quad M_B^{-1} = \begin{bmatrix} 0.9870 & -0.1471 & 0.1600 \\ 0.4323 & 0.5184 & 0.0493 \\ -0.0085 & 0.0400 & 0.9685 \end{bmatrix} \tag{2.2}$$

The chromatic-adaptation transform is a modified von Kries-type transformation with an exponential nonlinearity on the short-wavelength sensitive channel as given in Eqs. 2.3 through 2.6. In addition, the variable D is used to specify the degree of adaptation. D is set to 1.0 for complete adaptation or discounting the illuminant (as is typically the case for reflecting materials). D is set to 0.0 for no adaptation. D takes on intermediate values for various degrees of incomplete chromatic adaptation. Equation 2.7 allows calculation of such intermediate D values for various luminance levels and surround conditions.

$$R_c = [D(1.0/R_w) + 1 - D]R \tag{2.3}$$

$$G_c = [D(1.0/G_w) + 1 - D]G \tag{2.4}$$

$$B_c = [D(1.0/B_w^p) + 1 - D]B|^p \tag{2.5}$$

$$p = (B_w/1.0)^{0.0834} \tag{2.6}$$

$$D = F - F/[1 + 2(L_A^{1/4}) + (L_A^2)/300] \tag{2.7}$$

If B happens to be negative, then $B_c$ is also set to be negative. Similar transformations are also made for the source white since they are required in later calculations. Various factors must be calculated prior to further calculations as shown in Eqs. 2.8 through 2.12. These include a background induction factor, n, the background and chromatic brightness induction factors, $N_{bb}$ and $N_{cb}$, and the base exponential nonlinearity, z.

$$k = 1/(5L_A + 1) \tag{2.8}$$

$$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3} \tag{2.9}$$

$$n = Y_b / Y_w \tag{2.10}$$

$$N_{bb} = N_{cb} = 0.725(1/n)^{0.2} \tag{2.11}$$

$$z = 1 + F_{LL}n^{1/2} \tag{2.12}$$

The post-adaptation signals for both the sample and the source white are then transformed from the sharpened cone responses to the Hunt-Pointer-Estevez cone responses as shown in Eqs. 2.13 and 2.14, and illustrated in Fig. 1, prior to application of a nonlinear response compression.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_H M_B^{-1} \begin{bmatrix} R_c Y \\ G_c Y \\ B_c Y \end{bmatrix} \tag{2.13}$$

$$M_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00 & 0.00 & 1.00 \end{bmatrix} \quad M_H^{-1} = \begin{bmatrix} 1.9102 & -1.1121 & 0.2019 \\ 0.3710 & 0.6291 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix} \tag{2.14}$$

The post-adaptation cone responses (for both the sample and the white) are then calculated using Eqs. 2.15 through 2.17.

$$R'_a = \frac{40(F_L R'/100)^{0.73}}{\left[(F_L R'/100)^{0.73} + 2\right]} + 1 \tag{2.15}$$

$$G'_a = \frac{40(F_L G'/100)^{0.73}}{\left[(F_L G'/100)^{0.73} + 2\right]} + 1 \qquad (2.16)$$

$$B'_a = \frac{40(F_L B'/100)^{0.73}}{\left[(F_L B'/100)^{0.73} + 2\right]} + 1 \qquad (2.17)$$

## 2.3. Appearance Correlates

Preliminary red-green and yellow-blue opponent dimensions are calculated using Eqs. 2.18 and 2.19.

$$a = R'_a - 12G'_a/11 + B'_a/11 \qquad (2.18)$$

$$b = (1/9)(R'_a + G'_a - 2B'_a) \qquad (2.19)$$

The CIECAM97s hue angle, h, is then calculated from a and b using Eq. 2.20.

$$h = \tan^{-1}(b/a) \qquad (2.20)$$

Hue quadrature, H, and eccentricity factors, e, are calculated from the following unique hue data via linear interpolation between the following values for the unique hues:

Red: h = 20.14, e = 0.8, H = 0 or 400,
Yellow: h = 90.00, e = 0.7, H = 100,
Green: h = 164.25, e = 1.0, H = 200,
Blue: h = 237.53, e = 1.2. H = 300

Equations 2.21 and 2.22 illustrate calculation of e and H for arbitrary hue angles where the quantities subscripted 1 and 2 refer to the unique hues with hue angles just below and just above the hue angle of interest.

$$e = e_1 + (e_2 - e_1)(h - h_1)/(h_2 - h_1) \qquad (2.21)$$

$$H = H_1 + \frac{100(h - h_1)/e_1}{(h - h_1)/e_1 + (h_2 - h)/e_2} \tag{2.22}$$

The achromatic response is calculated as shown in Eq. 2.23 for both the sample and the white.

$$A = [2R'_a + G'_a + (1/20)B'_a - 2.05]N_{bb} \tag{2.23}$$

CIECAM97s Lightness, J, is calculated from the achromatic signals of the sample, A, and white, $A_W$, using Eq. 2.24.

$$J = 100(A/A_w)^{cz} \tag{2.24}$$

CIECAM97s Brightness, Q, is calculated from CIECAM97s lightness and the achromatic response for the white using Eq. 2.25.

$$Q = (1.24/c)(J/100)^{0.67}(A_w + 3)^{0.9} \tag{2.25}$$

Finally, CIECAM97s saturation, s; CIECAM97s chroma, C; and CIECAM97s colourfulness, M; are calculated using Eqs. 2.26 through 2.28, respectively.

$$s = \frac{50(a^2 + b^2)^{1/2}\, 100e(10/13)N_cN_{cb}}{R'_a + G'_a + (21/20)B'_a} \tag{2.26}$$

$$C = 2.44s^{0.69}(J/100)^{0.67n}(1.64 - 0.29^n) \tag{2.27}$$

$$M = CF_L^{0.15} \tag{2.28}$$

# 3. CONCLUSIONS

CIE TC1-34 recommends that the CIECAM97s model be evaluated as an interim solution to the problem of colour appearance specification. This model should help to address industrial needs by providing a single, CIE-recognized colour appearance model that represents the committee's best effort to bring together the best features of existing models. TC1-34 plans to subject this and other models to further testing. It is reasonable to expect that, at some future date, a more accurate and/or theoretically-based model might be developed.

## 3.1. CIECAM97s (Simple Version) Recommended Use

The CIECAM97s model should be adequate for most practical applications requiring use of colour appearance metrics or transformations more sophisticated than those provided by the CIELAB colour space. It does not allow for predictions of the influence of rod photoreceptors on colour appearance, the Helson-Judd effect, the Helmholtz-Kohlrausch effect, or the appearance of unrelated colours. A more comprehensive model, such as the planned CIECAM97c model should be considered when such phenomena are important.

CIECAM97s provides mathematical scales to correlate with various perceptual appearance attributes. As such, it does not explicitly construct a colour space. The CIECAM97s lightness, chroma, and hue correlates (J,C,h) can be used to construct a colour space by considering them as cylindrical coordinates as is done in the CIELAB colour space with $L^*$, $C^*_{ab}$, and $h_{ab}$. Alternatively, a brightness-colourfulness space could be constructed using CIECAM97s Q, M, and h as cylindrical coordinates. If a rectangular space is required, one can be constructed using the normal means for cylindrical-to-rectangular coordinate transformations (*i.e.*, J, Ccos(h), and Csin(h) or Q, Mcos(h), and Msin(h) could be used as rectangular coordinates.)

The question of colour-difference specification is often closely linked to that of colour appearance modeling. At this time, the CIECAM97s model has not been evaluated for use as a colour-difference space. While it would be possible to calculate a Euclidean colour-difference metric in either of the rectangular colour spaces described above, such a practice has not yet been shown to be better or worse than the current recommendation for CIE94 colour differences (CIE, 1995).

# 4. APPENDIX

## 4.1. Numerical Examples

Example calculations using the CIECAM97s are given for four samples in Table 4.1. Note that the magnitudes of the lightness and chroma scales in CIECAM97s are comparable to those of CIELAB. All calculations were performed using double precision. Slightly different results might be obtained with single precision calculations. (The hue angle calculation for near neutral colours (*e.g.*, Case 1) is a particular example in which large numerical differences can arise that have little visual meaning since the hue of an achromatic sample is truly undefined.) A Microsoft Excel spreadsheet with these example calculations for CIECAM97s can be found at <http://www.cis.rit.edu/people/faculty/fairchild/CAM.html>.

Table 4.1. Example calculations using CIECAM97s for four samples.

| | *Case 1* | *Case 2* | *Case 3* | *Case 4* |
|---|---|---|---|---|
| X | 19.01 | 57.06 | 3.53 | 19.01 |
| Y | 20.00 | 43.06 | 6.56 | 20.00 |
| Z | 21.78 | 31.96 | 2.14 | 21.78 |
| $X_w$ | 95.05 | 95.05 | 109.85 | 109.85 |
| $Y_w$ | 100.00 | 100.00 | 100.00 | 100.00 |
| $Z_w$ | 108.88 | 108.88 | 35.58 | 35.58 |
| $L_A$ (cd/m$^2$) | 318.31 | 31.83 | 318.31 | 31.83 |
| F | 1.0 | 1.0 | 1.0 | 1.0 |
| D | 0.997 | 0.890 | 0.997 | 0.890 |
| $Y_b$ | 20.0 | 20.0 | 20.0 | 20.0 |
| c | 0.69 | 0.69 | 0.69 | 0.69 |
| $N_c$ | 1.0 | 1.0 | 1.0 | 1.0 |
| $F_{LL}$ | 1.0 | 1.0 | 1.0 | 1.0 |
| k | 0.0006 | 0.0062 | 0.0006 | 0.0062 |
| $F_L$ | 1.17 | 0.54 | 1.17 | 0.54 |

| | | | | |
|---|---|---|---|---|
| $n$ | 0.20 | 0.20 | 0.20 | 0.20 |
| $N_{bb}$ | 1.00 | 1.00 | 1.00 | 1.00 |
| $N_{cb}$ | 1.00 | 1.00 | 1.00 | 1.00 |
| $z$ | 1.45 | 1.45 | 1.45 | 1.45 |
| $R$ | 0.94 | 1.33 | 0.70 | 0.94 |
| $G$ | 1.04 | 0.75 | 1.32 | 1.04 |
| $B$ | 1.09 | 0.75 | 0.29 | 1.09 |
| $R_w$ | 0.94 | 0.94 | 1.19 | 1.19 |
| $G_w$ | 1.04 | 1.04 | 0.90 | 0.90 |
| $B_w$ | 1.09 | 1.09 | 0.34 | 0.34 |
| $p$ | 1.01 | 1.01 | 0.91 | 0.91 |
| $R_c$ | 1.00 | 1.41 | 0.58 | 0.81 |
| $G_c$ | 1.00 | 0.72 | 1.46 | 1.14 |
| $B_c$ | 1.00 | 0.69 | 0.86 | 2.70 |
| $R_{cw}$ | 1.00 | 0.99 | 1.00 | 1.02 |
| $G_{cw}$ | 1.00 | 1.00 | 1.00 | 0.99 |
| $B_{cw}$ | 1.00 | 1.01 | 1.00 | 0.93 |
| $R'$ | 20.0 | 51.2 | 5.58 | 18.9 |
| $G'$ | 20.0 | 39.3 | 7.70 | 23.0 |
| $B'$ | 20.0 | 29.5 | 5.80 | 53.0 |
| $R'_w$ | 100.0 | 99.7 | 100.0 | 101.0 |
| $G'_w$ | 100.0 | 100.2 | 100.0 | 99.4 |
| $B'_w$ | 100.0 | 101.0 | 99.8 | 93.3 |
| $R'_a$ | 6.90 | 7.56 | 3.55 | 4.46 |
| $G'_a$ | 6.90 | 6.57 | 4.17 | 4.94 |
| $B'_a$ | 6.90 | 5.64 | 3.62 | 7.70 |
| $R'_{aw}$ | 15.4 | 10.7 | 15.4 | 10.7 |
| $G'_{aw}$ | 15.4 | 10.7 | 15.4 | 10.7 |
| $B'_{aw}$ | 15.4 | 10.7 | 15.3 | 10.3 |
| $a$ | -0.0005 | 0.90 | -0.67 | -0.23 |

| | | | | |
|---|---|---|---|---|
| b | -0.0004 | 0.32 | 0.05 | -0.67 |
| h | 219.4 | 19.35 | 175.4 | 250.8 |
| H | 270 | 399 | 218 | 307 |
| $H_c$ (Red) | 0 | 99 | 0 | 7 |
| $H_c$ (Yellow) | 0 | 0 | 0 | 0 |
| $H_c$ (Green) | 30 | 0 | 82 | 0 |
| $H_c$ (Blue) | 70 | 1 | 18 | 93 |
| e | 1.15 | 0.80 | 1.03 | 1.16 |
| A | 18.99 | 19.92 | 9.40 | 12.19 |
| $A_w$ | 44.80 | 30.54 | 44.80 | 30.62 |
| J | 42.44 | 65.27 | 21.04 | 39.88 |
| Q | 32.86 | 31.88 | 20.53 | 22.96 |
| s | 0.14 | 146.98 | 232.16 | 180.56 |
| C | 0.47 | 61.97 | 72.99 | 66.85 |
| M | 0.49 | 56.52 | 74.70 | 60.98 |

## 4.2. Inverting the CIECAM97s Model

Steps for using the CIECAM97s model in the reverse direction for corresponding-colours calculations or colour-reproduction applications follow.

Starting Data:

Q or J, M or C, H or h

$A_w$, n, z, $F_L$, $N_{bb}$, $N_{cb}$ Obtained Using Forward Model

Surround Parameters: F, c, $F_{LL}$, $N_c$

Luminance Level Parameters: $L_A$, D

Unique Hue Data:

Red: h = 20.14, e = 0.8

Yellow: h = 90.00, e = 0.7

Green: h = 164.25, e = 1.0

Blue: h = 237.53, e = 1.2

(1) From Q Obtain J (if necessary)

$$J = 100(Qc/1.24)^{1/0.67}/(A_w + 3)^{0.9/0.67} \quad (4.10$$

(2) From J Obtain A

$$A = (J/100)^{1/c\alpha} A_w \quad (4.2)$$

(3) Using H, Determine $h_1$, $h_2$, $e_1$, $e_2$ (if h is not available)

$e_1$ and $h_1$ are the values of e and h for the unique hue having the nearest lower value of h and $e_2$ and $h_2$ are the values of e and h for the unique hue having the nearest higher value of h.

(4) Calculate h (if necessary)

$$h = [(H - H_1)(h_1/e_1 - h_2/e_2) - 100h_1/e_1] / [(H - H_1)(1/e_1 - 1/e_2) - 100/e_1] \quad (4.3)$$

$H_1$ is 0, 100, 200, or 300 according to whether red, yellow, green, or blue is the hue having the nearest lower value of h.

(5) Calculate e

$$e = e_1 + (e_2 - e_1)(h - h_1)/(h_2 - h_1) \tag{4.4}$$

$e_1$ and $h_1$ are the values of e and h for the unique hue having the nearest lower value of h and $e_2$ and $h_2$ are the values of e and h for the unique hue having the nearest higher value of h.

(6) Calculate C (if necessary)

$$C = M/F_L^{0.15} \tag{4.5}$$

(7) Calculate s

$$s = C^{1/0.69} / \left[2.44(J/100)^{0.67n}(1.64 - 0.29^n)\right]^{1/0.69} \tag{4.6}$$

(8) Calculate a and b

$$a = s(A/N_{bb} + 2.05) / \left\{\left[1 + (\tan h)^2\right]^{1/2}\left[50000eN_cN_{cb}/13\right] + s\left[(11/23) + (108/23)(\tan h)\right]\right\} \tag{4.7}$$

In calculating $\left[1 + (\tan h)^2\right]^{1/2}$ the result is taken as:

positive for $0° \le h < 90°$

negative for $90° \le h < 270°$

positive for $270° \le h < 360°$.

$$b = a(\tan h) \tag{4.8}$$

(9) Calculate $R'_a$, $G'_a$, and $B'_a$

$$R'_a = (20/61)(A/N_{bb} + 2.05) + (41/61)(11/23)a + (288/61)(1/23)b \tag{4.9}$$

$$G'_a = (20/61)(A/N_{bb} + 2.05) - (81/61)(11/23)a - (261/61)(1/23)b \tag{4.10}$$

$$B'_a = (20/61)(A/N_{bb} + 2.05) - (20/61)(11/23)a - (20/61)(315/23)b \tag{4.11}$$

(10) Calculate R', G', and B'

$$R' = 100[(2R'_a - 2)/(41 - R'_a)]^{1/0.73} \quad (4.12)$$

$$G' = 100[(2G'_a - 2)/(41 - G'_a)]^{1/0.73} \quad (4.13)$$

$$B' = 100[(2B'_a - 2)/(41 - B'_a)]^{1/0.73} \quad (4.14)$$

If $R'_a$-1 < 0 use:

$$R' = -100[(2 - 2R'_a)/(39 + R'_a)]^{1/0.73} \quad (4.15)$$

and similarly for the G' and B' equations.

(11) Calculate $R_cY$, $G_cY$, and $B_cY$

$$\begin{vmatrix} R_cY \\ G_cY \\ B_cY \end{vmatrix} = M_B M_H^{-1} \begin{vmatrix} R'/F_L \\ G'/F_L \\ B'/F_L \end{vmatrix} \quad (4.16)$$

(12) Calculate $Y_c$

$$Y_c = 0.43231 R_cY + 0.51836 G_cY + 0.04929 B_cY \quad (4.17)$$

(13) Calculate $(Y/Y_c)R$, $(Y/Y_c)G$, and $(Y/Y_c)^{1/p}B$

$$(Y/Y_c)R = (Y/Y_c)R_c/[D(1/R_w) + 1 - D] \quad (4.18)$$

$$(Y/Y_c)G = (Y/Y_c)G_c/[D(1/G_w) + 1 - D] \quad (4.19)$$

$$(Y/Y_c)^{1/p} B = [|(Y/Y_c)B_c|]^{1/p}/[D(1/B_w^p) + 1 - D]^{1/p} \quad (4.20)$$

If $(Y/Y_c)B_c$ <0.0 then $(Y/Y_c)^{1/p}B$ is also set to be negative.

(14) Calculate Y'

$$Y' = 0.43231 YR + 0.51836 YG + 0.04929 (Y/Y_c)^{1/p} BY_c \quad (4.21)$$

(15) Calculate X'', Y'' and Z''

$$\begin{vmatrix} X' \\ Y'' \\ Z' \end{vmatrix} = M_B^{-1} \begin{vmatrix} Y_c(Y/Y_c)R \\ Y_c(Y/Y_c)G \\ Y_c(Y/Y_c)^{1/p} B/(Y'/Y_c)^{(1/p-1)} \end{vmatrix} \tag{4.22}$$

Note: X'', Y'', and Z'' are equal to the desired X, Y, and Z to a very close approximation. This is because Y' differs from Y since $(Y/Y_c)^{1/p}BY_c$ is used instead of YB. However this is multiplied by 0.04929 so the difference is small.

## 5. REFERENCES


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